

EPISODIC GREENHOUSE CLIMATES ON MARS. V. C. Gulick^{1,2}, R. M. Haberle¹, and C. P. McKay¹, ¹NASA/Ames Research Center; MS 245-3; Moffett Field, CA 94035. ²NMSU Dept. Astronomy; Las Cruces NM 88003; gulick@barsoom.arc.nasa.gov

Baker *et al.* [1] proposed that a variety of anomalous fluvial and glacial features of varying ages on Mars could be explained by transient greenhouse atmospheres produced in association with ephemeral lakes or seas resulting from outflow channel formation. In this hypothesis, the discharge of the outflow channels is associated with the release of several bars of CO₂ into the martian atmosphere. During the resulting greenhouse period, fluvial valleys, such as those on the flanks of the volcano Alba Patera, and glacial features, such as eskers in the southern highlands are formed. The transient greenhouse hypothesis thus attempts to explain anomalous features which formed long after the putative warm, wet early martian climate had decayed.

Several aspects of the Baker *et al.* hypothesis have been questioned. Typical concerns include, where do the pulses of CO₂ come from and how are they released and recycled? Is an injection of several bars of CO₂ sufficient to raise the global temperatures enough to permit atmospheric transport of water? Would the transient greenhouse atmosphere last long enough to permit sufficient erosion and water transport to occur? Gulick *et al.* [2] address these and other questions relating to the atmospheric effects of the Baker *et al.* hypothesis. Here we report on our analysis of these aspects of the hypothesis.

Greenhouse

We applied a Mars climate evolution model [3] to explore the effects of adding pulses of CO₂ to the atmosphere at various times in Mars' history. Transport and exchange between the atmosphere and CO₂ reservoirs, including the poles, carbonates, and the regolith are modeled, as is atmospheric escape. Models with and without atmospheric CO₂ condensation are considered. The calculation begins with a starting inventory of 1 bar of CO₂ at 4.5 Ga. Results are not sensitive to the initial inventory. Mars quickly equilibrates into a state like of that of today where the poles buffer the atmosphere. Then at 1, 2, or 3 Ga a pulse of CO₂ ranging from 1 to 4 bars is instantaneously added to the atmosphere. The pulses are accompanied by surface water, assumed to cover between 5 and 30% of Mars' surface area.

After the CO₂ injection at 1 Ga or 2 Ga the atmosphere becomes unbuffered and the surface temperature rapidly rises. Since the polar cap contributes its CO₂ to the atmosphere once the temperatures first rise, the total atmospheric CO₂ increase is larger than the pulse size. The regolith reservoir grows in size with the increase in pressure, but the temperature forcing on the regolith resulting from the pressure increase limits the response.

With warmer temperatures and surface water, the weathering rates increase and the atmospheric CO₂ starts to decay. The growth of the carbonate reservoir is rapid after

the pulse. As the atmospheric CO₂ inventory falls, so does the surface temperature. In all cases, except for pulses injected at 1 Ga with 5% water coverage, the atmosphere eventually collapses, polar caps form, and the atmosphere returns to the buffered regime by the present epoch. Therefore, except for this one case, the CO₂ pulse model meets the observational constraint that polar caps exist on present day Mars. This constraint is really a statement that CO₂ pulses must be accompanied by a sufficiently large areal extent of surface water to remove the injected carbon dioxide.

CO₂ pulses in excess of 2 bars at 3 Ga and 1 bar at 2 Ga, and about 1 bar at 1 Ga are sufficient to raise mean global temperatures above 240 to 250 K for periods in excess of 106 years. Such pulses also produce modern climates consistent with the current Mars.

Atmospheric Vapor Transport

To determine if the transient greenhouse climates may be associated with vapor transport, we model the sublimation of the frozen outflow channel discharges. The model begins with initially dry air that blows over the sea and reaches saturation as the underlying ice sublimates. The rate of sublimation of the ice sheet depends exponentially on the temperature and somewhat on the wind speed. For current martian conditions and wind speeds of 1 to 5 m/sec, sublimation rates are in the range of 0.3 to 3 cm/year. For mean conditions 25 and 50 K warmer than present, the sublimation rates are 10 and 100 times larger, respectively. The saturated air cools as it is lifted upward and part of the entrained water vapor condenses as snow. The fraction of water that is deposited as snow depends on the lapse rate and the height of the ascent. That is, the difference between the elevation of the snowfield and the surface of the sea.

For current martian conditions, the snow accumulation rate over a 2 km altitude change is approximately 1 cm/yr of equivalent water, if the snow accumulation area is equivalent to the area of the sea. This mechanism can operate under conditions in which global temperatures are still below freezing, yet a substantial amount of water can be transported. Drawing upon terrestrial erosion rates, we conclude that global mean temperatures in excess of 240 to 250 K are sufficient to transport water volumes needed to erode observed fluvial valleys on Mars. Thus several bar and larger pulses of CO₂ warm the atmosphere sufficiently to allow for substantial water vapor transport.

Sources

A central tenant of the Baker *et al.* hypothesis is that the discharge of the outflow channels is associated with the release of large amounts of CO₂ into the martian atmosphere. The authors discuss associated volcanism, release of gas dissolved in the ground water, adsorbed in the regolith,

and resident in the polar caps as possible sources and estimate that up to 4 bars of CO_2 may be released by these mechanisms.

If the outflow channels are indeed associated with massive hydrothermal systems [1, 4] there are additional possible CO_2 sources. Magmatic gases commonly dissolve into ground water. The outflow channel discharges themselves may have been especially CO_2 rich. Acidic hydrothermal fluids may have dissolved carbonate deposits in the subsurface before the discharge event, resulting in CO_2 charged groundwater. Alternatively acidic discharged fluids might have decomposed near-surface carbonate deposits as the water reinfiltated the surface after release. To date there has been no quantitative investigation of such mechanisms.

Climate Stability

The Baker *et al.* hypothesis focused on single ocean-forming events, but suggested that multiple outflow channel episodes might lead to different oceans at different periods in Mars' geologic history. Multiple ocean forming events might cycle the martian climate system between alternating periods of warm and cool conditions.

Figure 1 illustrates the process. Point A in the figure represents conditions prior to the first ocean-forming event. A permanent polar cap exists and the surface pressure is less than it is today since the sun is less luminous. When the first ocean-forming event occurs, it vaporizes the cap and/or it releases dissolved CO_2 into the atmosphere. In order for the climate to transition to a warmer state, the total amount released must exceed the difference between the pressure at point B and point A. Less than this and the cap reforms and the system returns to point A. More than this and the system moves up the curve to, say, point C where the climate stabilizes in a warmer temperature regime. The exact location of point C will depend on the amount of CO_2 available to the system. While in this new regime, weathering gradually draws down the atmosphere until reaching point B. With additional weathering the climate collapses (point B is unstable), and the system returns to point A. If the time between ocean-forming events is geologically long, then solar brightening shifts up the solid curve in Figure 1.

When the next ocean-forming event occurs (point D), the process is repeated (again, only if the amount released is greater than the difference between point E and point D), but the "warm" regime (point F) is now cooler than the

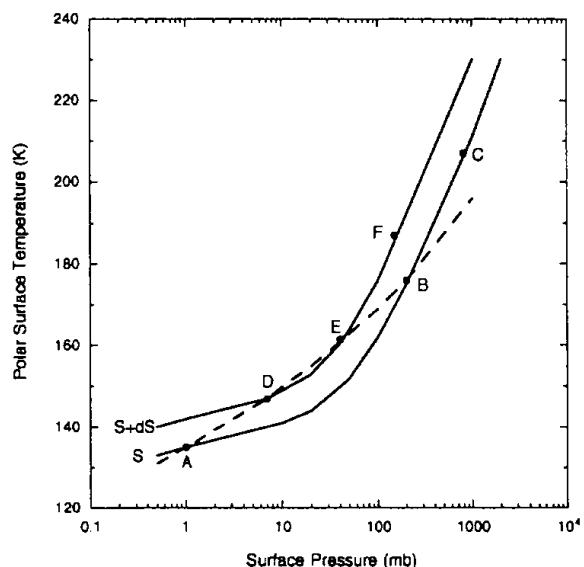


Figure 1. A schematic illustration of ocean-driven climate cycling on Mars. Solid lines represent annual mean polar surface temperatures. Solid line labeled S (S+DS) corresponds to first (second) ocean-forming event. The dashed line represents the CO_2 frost point. Permanent polar caps are permitted at the intersections of the solid and dashed curves. See text for details.

previous one because of the irreversible loss of CO_2 to the carbonate reservoir. Thus, multiple ocean-forming events can cycle the Martian climate system between warm and cool regimes, but each successive event will have a cooler climate unless the carbonate reservoir is somehow recycled as well.

References: [1] Baker, V. *et al.* (1991) *Nature*, **352**, 589–594. [2] Gulick, V. *et al.* (1997) *Icarus*, in press. [3] Haberle *et al.* (1994) *Icarus*, **109**, 102–120. [4] Baker, V. *et al.* (1993) in *Resources of Near Earth Space*, Univ. of Ariz. Press, 765–797.